

Study of a narrow $\pi^+\pi^-$ peak at about 755 MeV/ c^2 in $\bar{p}n \rightarrow 2\pi^+3\pi^-$ annihilation at rest

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Abstract

A narrow peak in the $\pi^+\pi^-$ mass distribution was seen by the Rome-Syracuse Collaboration in $\bar{p}n \rightarrow 2\pi^+3\pi^-$ annihilation at rest 39 years ago. The reanalysis of this peak finds a mass of 757.4 ± 2.6 MeV/ c^2 and a width slightly narrower than the experimental resolution. The evidence of the peak is 5.2 standard deviations. This state is generated in $(12.4 \pm 2.4)\%$ of the $\bar{p}n \rightarrow 2\pi^+3\pi^-$ annihilations at rest. No spin analysis is possible with the statistics of the experiment. *PACS:* 13.60Le, 13.75.Cs, 14.40.Cs

About forty years ago, the Rome-Syracuse Collaboration collected a sample of 1496 annihilation at rest in deuterium bubble chamber

$$\bar{p}n \rightarrow 2\pi^+3\pi^-. \quad (1)$$

This sample was made by $\bar{p}d \rightarrow p2\pi^+3\pi^-$ annihilations selected with the cut at 150 MeV/ c^2 on the proton momentum. 665 events were reconstructed at Rome and 831 events at Syracuse.

The $\pi^+\pi^-$ mass distribution of this sample was published in 1970 with a binning of 20 MeV/ c^2 [1]. It showed an excess of about 100 combinations

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in the interval $740 < m < 760 \text{ MeV}/c^2$. The structure of this excess is more evident in the distribution with $10 \text{ MeV}/c^2$ shown in Fig. 1¹. However, the Collaboration did not claim the observation of a *new resonance* because the properties of the annihilation (1) were not known at that time, and the coincidence of the peak with the ρ^0 mass suggested that it was generated by the interference of the ρ^0 meson with another channel.

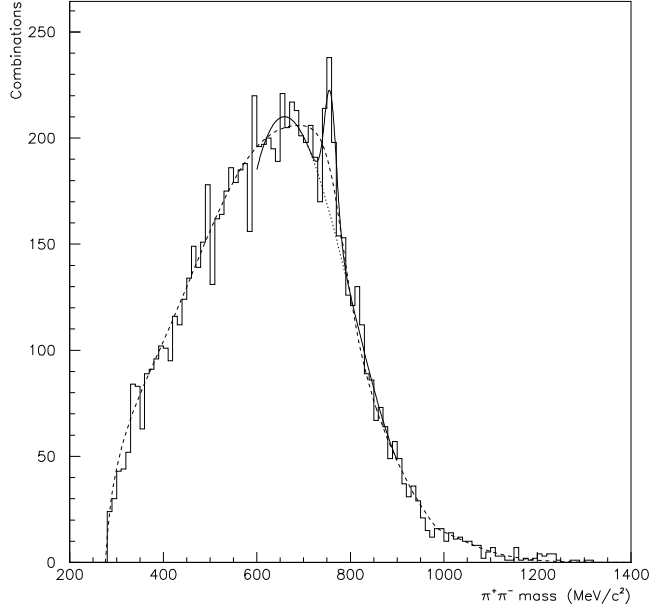


Figure 1: $\pi^+\pi^-$ mass distribution at 10 MeV binning of the $\bar{p}n \rightarrow 2\pi^+3\pi^-$ annihilation at rest. The dashed curve is the prediction of the fit discussed in Ref. [3]. The solid curve is the result of the fit D. The dotted curve is the third degree polynomial background predicted by fit D under the peak.

The properties of the annihilation (1) were understood at the beginning of the '90s. A reanalysis of the same Rome-Syracuse sample [2, 3] proved that the annihilation (1) is dominated by the channel

$$\bar{p}n \rightarrow f_0(1370)\pi^-,$$

$f_0(1370)$ being a scalar meson [4] that decays into $\rho\rho$ and $S_w S_w$, where S_w is

¹ The $\pi^+\pi^-$ distribution with this binning was not previously published.

the symbol for the $\pi^+\pi^-$ $I = 0$ S-wave interaction².

This reanalysis was able to reproduce satisfactorily ten experimental distributions, but failed to reproduce the $\pi^+\pi^-$ distribution in the interval $720 \leq m \leq 770$ MeV/ c^2 , as shown by the dashed curve in Fig. 1 that is reporting the prediction plotted in Fig. 3b of Ref. [3].

A year after the proof of the $f_0(1370)$ dominance in annihilation (1) [2], the OBELIX Collaboration reported the results of the study of the annihilation at low momenta [5]

$$\bar{n}p \rightarrow 3\pi^+2\pi^-. \quad (2)$$

This analysis confirmed the $f_0(1370)\pi^+$ dominance, followed by the $f_0(1370)$ decay into $\rho\rho$ and S_wS_w , but did not show any peak at about 755 MeV/ c^2 in the $\pi^+\pi^-$ distribution.

A structure seen in the annihilation (1) should also be seen in the charge conjugate annihilation (2). Therefore, at that time, I supposed that the peak shown by Fig. 1 could be generated by an exceptional fluctuation higher than 4 standard deviations (SD). But, after the OBELIX paper, Troyan *et al.* observed in $np \rightarrow np\pi^+\pi^-$ interactions at 5.2 GeV/ c a narrow $\pi^+\pi^-$ peak at 757 ± 5 MeV/ c^2 , with significance 8.5 SD [6]. This result challenged the interpretation of a statistical fluctuation. For this reason, I have reanalysed the Rome-Syracuse sample.

Table 1 reports two χ^2 fits of the $\pi^+\pi^-$ mass distribution shown in Fig. 1, carried out using the MINUIT package [7] in the interval $600 \leq m \leq 900$ MeV/ c^2 . The distribution has been parametrized with the sum of a third degree polynomial and a Gaussian

$$D(m) = P_3(m - m_0) + \frac{N_p}{\sqrt{2\pi}\sigma_p} e^{-\frac{(m - M_p)^2}{2\sigma_p^2}}. \quad (3)$$

The polynomial has been chosen to be a function of the difference $m - m_0$ with $m_0 = 750$ MeV/ c^2 to reduce the correlations between the coefficients of the polynomial and the number of combinations N_p .

In Table 1 fit A reports the results of the fit of the $\pi^+\pi^-$ distribution shown in Fig. 1 with the resolution σ_p free. Its χ^2 proves that a third degree polynomial is enough for a good fit in the region of interest. The signal significance is 4.6 SD, but this fit is unphysical because of its resolution: the

² This interaction was called σ in Refs. [2, 3]. Now I prefer to use the symbol S_w for it to avoid any confusion with the debated resonance $\sigma(600)$ [4].

Table 1: Results of the χ^2 fits of the distribution shown in Fig. 1 in the interval $600 \leq m \leq 900$ MeV/ c^2 . Fit A is the fit with σ_p free. Fit B is the fit with σ_p fixed at the experimental value 12.74 MeV/ c^2 .

Fit	A	B
N_p (combinations)	152 ± 33	188 ± 37
M_p (MeV/ c^2)	755.4 ± 1.9	756.3 ± 2.5
σ_p (MeV/ c^2)	7.7 ± 1.7	12.74
$N_p/\Delta N_p$	4.6	5.1
χ^2	14.7	19.6
d.o.f	24	25
$\chi^2/\text{d.o.f.}$	0.61	0.78

Rome-Syracuse Collaboration estimated that the experimental resolution of the $\pi^+\pi^-$ masses had a FWHM = 30 MeV/ c^2 [1]³. Therefore, the physical resolution cannot be lower than $\sigma_p = 12.74$ MeV/ c^2 .

Fit B in Table 1 reports the results of the fit of the same distribution with the resolution fixed at 12.74 MeV/ c^2 . This result proves that the peak width is compatible with the experimental resolution and improves the significance of the signal to 5.1 SD.

However, the significance of a χ^2 fit may depend on the distribution binning. For this reason, the fits have been repeated using the values of the $\pi^+\pi^-$ masses that were maintained on punched card support⁴. The distribution of these masses is in full agreement with that reported in Fig. 1. In addition, the study of these data has proved that there are no event duplications and that the peak is visible in both the Rome and the Syracuse subsamples. This excludes that the peak was generated by a systematic error in the event reconstruction because the two institutions used two different reconstruction program packages.

The knowledge of all the $\pi^+\pi^-$ masses in the events has also allowed to repeat the fit with an unbinned log-likelihood

$$\mathcal{L} = -\ln \left[\prod_n \frac{D(m_n)}{\int_{600}^{900} D(m) dm} \right],$$

³ Actually, Ref. [1] gave the value FWHM = 300 MeV/ c^2 , but this was a misprint.

⁴ These data were already used in an analysis of the Bose-Einstein correlations [8].

where the product is on the $\pi^+\pi^-$ mass combinations in the interval $600 \leq m_n \leq 900 \text{ MeV}/c^2$, and $D(m)$ is the function (3).

The results of these fits are reported in Table 2. The fits C and D in this table have been performed respectively with σ_p free and with $\sigma = 12.74 \text{ MeV}/c^2$ and confirm the results of fits A and B. In the following, I will use the results of fit D because it takes into account both the known experimental resolution and how the $\pi^+\pi^-$ masses are distributed inside the intervals.

Table 2: Results of the unbinned maximum likelihood fits in the interval $600 \leq m \leq 900 \text{ MeV}/c^2$. Fit C is the fit with σ_p free. Fit D is the fit with $\sigma_p = 12.74 \text{ MeV}/c^2$.

Fit	C	D
N_p (combinations)	147 ± 35	186 ± 36
M_p (MeV/ c^2)	756.7 ± 1.9	757.4 ± 2.6
σ_p (MeV/ c^2)	8.1 ± 2.1	12.74
$N_p/\Delta N_p$	4.2	5.2

The study of the correlations between the $\pi^+\pi^-$ combinations in the peak and the other $\pi^+\pi^-$ masses has shown no evidence for a double peak production. Therefore, the events under the peak are assumed to be generated by the channel

$$\bar{p}n \rightarrow P(757)\pi^+2\pi^-; \quad P(757) \rightarrow \pi^+\pi^-. \quad (4)$$

The punched cards maintained also the $\pi^+\pi^+$ and $\pi^-\pi^-$ mass distributions. The knowledge of all the ten $\pi\pi$ masses has allowed to reconstruct the 3π and 4π masses and other variables. This analysis has fitted several $\pi^+\pi^-$ distributions obtained by imposing cuts on these variables, but none of them was able to significantly increase the evidence for the signal. The conclusion is that the statistics of the Rome-Syracuse sample is too low to understand how the signal is correlated with the other three pions. In particular, no spin analysis is possible.

The results of the fit D allow to draw the following conclusions:

- The $\pi^+\pi^-$ mass distribution in the $\bar{p}n \rightarrow 2\pi^+3\pi^-$ annihilation at rest shows a peak at $757.4 \pm 2.6 \text{ MeV}/c^2$ with significance of 5.2 SD.
- The mass of this peak is in agreement with the value $757 \pm 5 \text{ MeV}/c^2$ of a resonance observed by Troyan *et al.* [6].

- The width of the observed peak is compatible with the experimental resolution.
- The fraction of events with this peak in reaction (1) is

$$f = \frac{N_p}{1496} = (12.4 \pm 2.4)\%.$$

- The frequency of the $\bar{p}n \rightarrow 2\pi^+3\pi^-$ annihilation at rest is $F_{5\pi} = (6.9 \pm 0.5)\%$ [3]. Therefore, the frequency of the channel (4) is

$$F_{P3\pi} = \frac{N_p}{1496} F_{5\pi} = (0.86 \pm 0.18)\%.$$

- The spin-parity of this peak cannot be measured using the Rome-Syracuse data.
- An analog peak was not observed in the charge conjugate annihilation (2) by the OBELIX Collaboration [5]. Therefore, other experimental analyses are needed for confirming or disproving the existence of this state.

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